# Challenges for operational mitigation of contrails

## *Meteorological information needs*

**Steven L. Baughcum** (Steven.L.Baughcum@boeing.com)
**Timothy F. Rahmes**
**September 7, 2022**

# Approach

Persistent contrails – interaction of aircraft emissions with weather

**Contrail formation (Schmidt-Appleman criteria)**

- Ambient temperature/pressure/humidity
- Propulsion Efficiency
- Fuel – heat of combustion, EI(H2O)

**Contrail Persistence**

- RHi > 100%

## Contrail Impact

- Evolving weather system (temperature, humidity, winds)
- Contrail microphysics (number of ice particles formed initially)

# Context for mitigating contrail impact

*What are the options?*

- **Reduce the number of ice particles**
    - Modified combustion: Advanced combustors can produce less soot
    - Change fuel composition: Lower aromatics produce less soot (activated soot act as ice nuclei)
    - Drastic engine/airframe changes: hydrogen fuel, fuel cells, capture exhaust water, etc.
- **Avoid cold ice-supersaturated layers (ISSL):** If we avoid regions with RHI>100% that meet the Schmidt-Appleman criteria, we won’t create persistent contrails.
    - Can we identify the persistent contrails with the greatest impact robustly?
        - In research mode?
        - In operational forecasts?
- Account for those ISSL that would have evolved into natural cirrus

# Better Weather Forecasting at Altitude

- Any model analyzing aircraft-induced cloudiness requires ***reliable weather forecasting at altitude***:
  - Reliable temperatures and relative humidity predictions
  - Reliable predictions of ice supersaturated conditions
- In-situ measurements at cruise altitudes (currently available data are limited)
  - Research aircraft field missions (NASA, NOAA, NCAR, DLR, FAAM, etc.)
  - MOZAIC/IAGOS (a few airplanes on a few routes over 25 years)
  - Radiosonde vertical profiles

- Further measurements are required to test, evaluate, and improve such predictions -> Ultimately to assimilate into forecast models

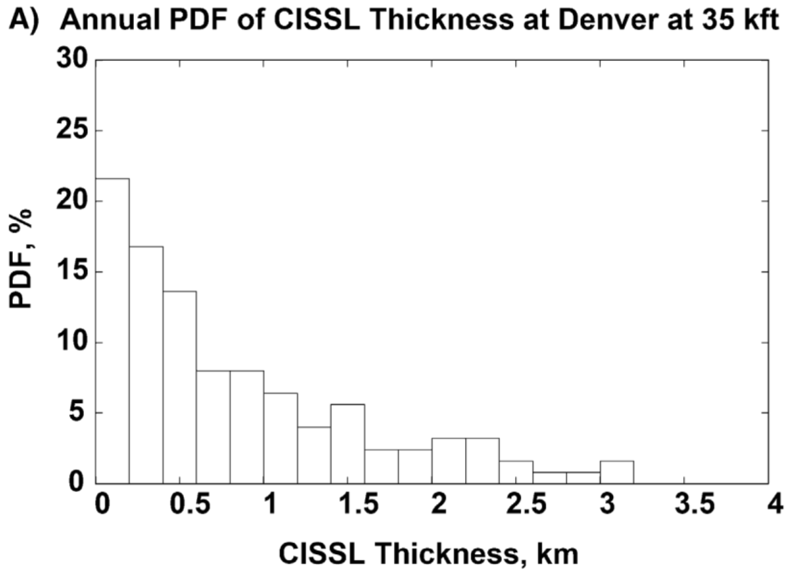
# What do Radiosondes Tell us

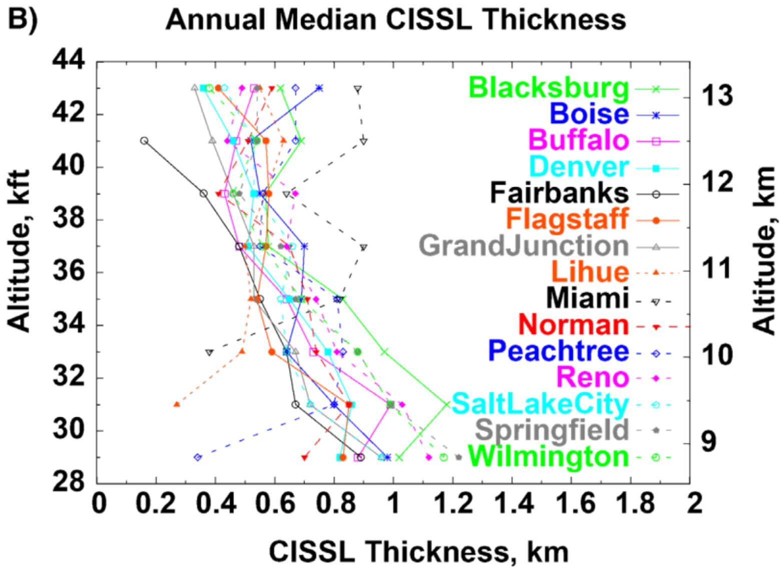
- Temperature and time lag response corrections necessary for radiosonde data but provide detailed data on vertical humidity distribution

- Mannstein, Spichtinger and Gierens analyzed European radiosonde data, applied instrument corrections and showed that ice supersaturated regions were generally less than 1 km thick vertically. Similar results on US data (below).

- 80% of the time, the radiosonde data indicate that there will only be one contrail ice supersaturation layer (CISSL)(ISSL in which a contrail forms and persists)

Contrail Ice Supersaturation Layer Thickness (derived from US radiosonde data, 5 year period)




Baughcum, Danilin, Milosevich, Heymsfield (2009)

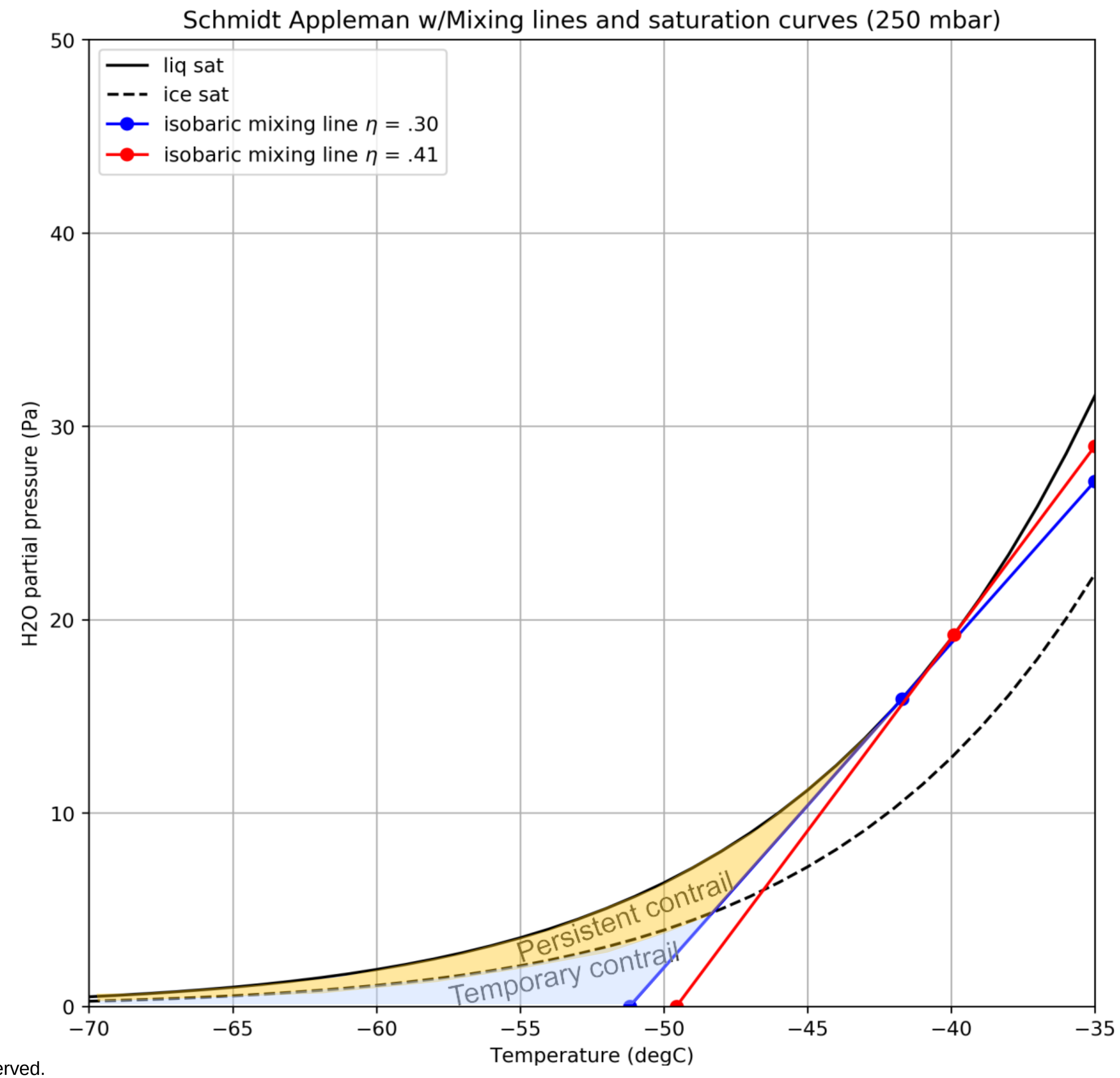
# MOZAIC/IAGOS In-service Humidity Observations

- Valuable source of humidity measurements at cruise altitudes from commercial airplanes in service
  - Extensive calibration protocol over 27 years
  - Limited number of airplanes (5 for MOZAIC, approximately 10 for IAGOS)
  - Limited routes
  - Best available data to date

Gierens and co-workers have analyzed IAGOS data and compared with model predictions

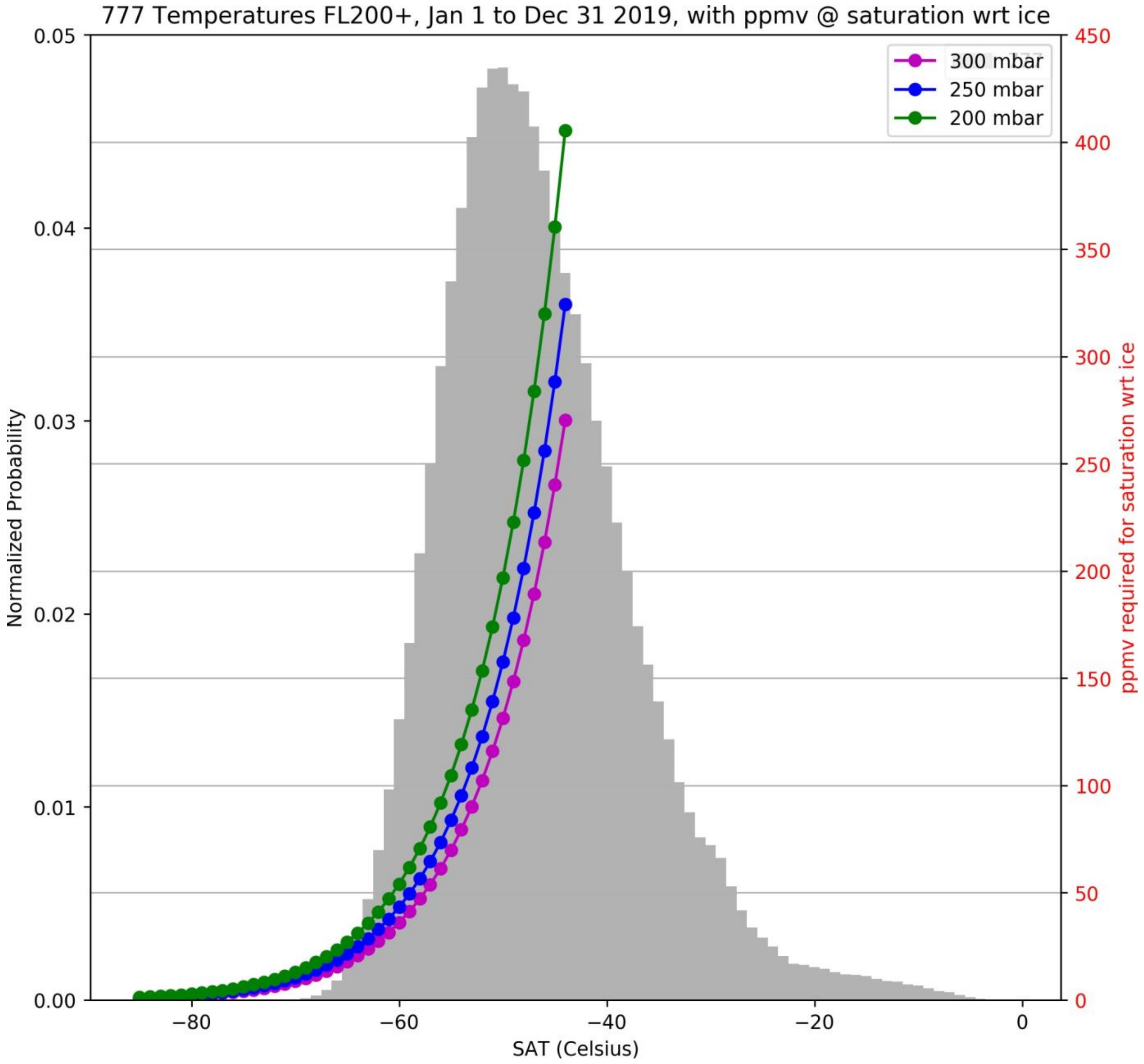
- Contrail formation in the ECMWF forecasts are predicted well suggesting that temperatures are predicted well
- Relative humidity and hence persistent contrail formation is not adequately predicted when compared to the IAGOS observations

# We need to consider the persistent contrails which have the highest impact

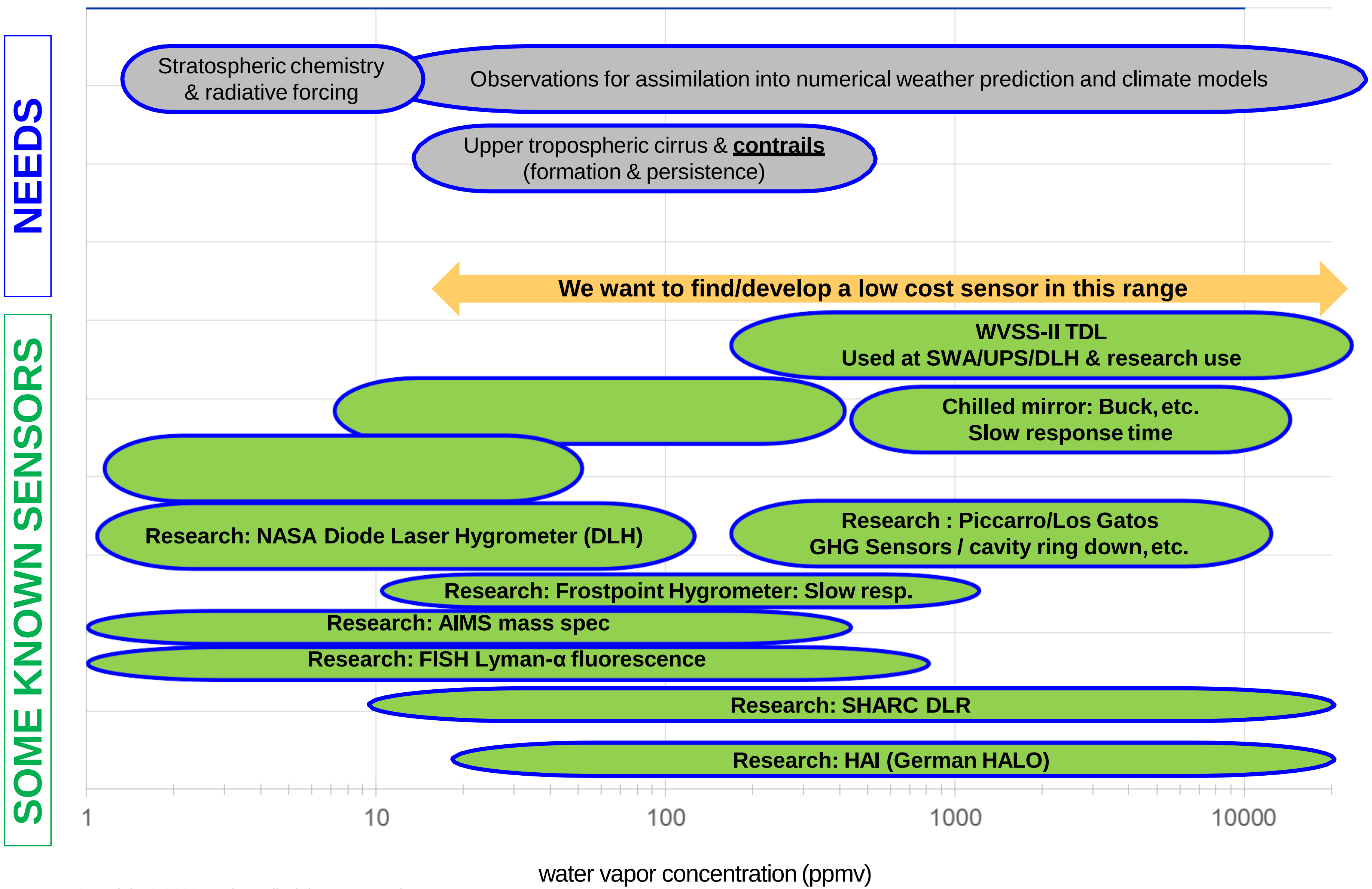


# We know *in situ* temperatures fairly well
## *(use T to characterize ice supersaturation)*

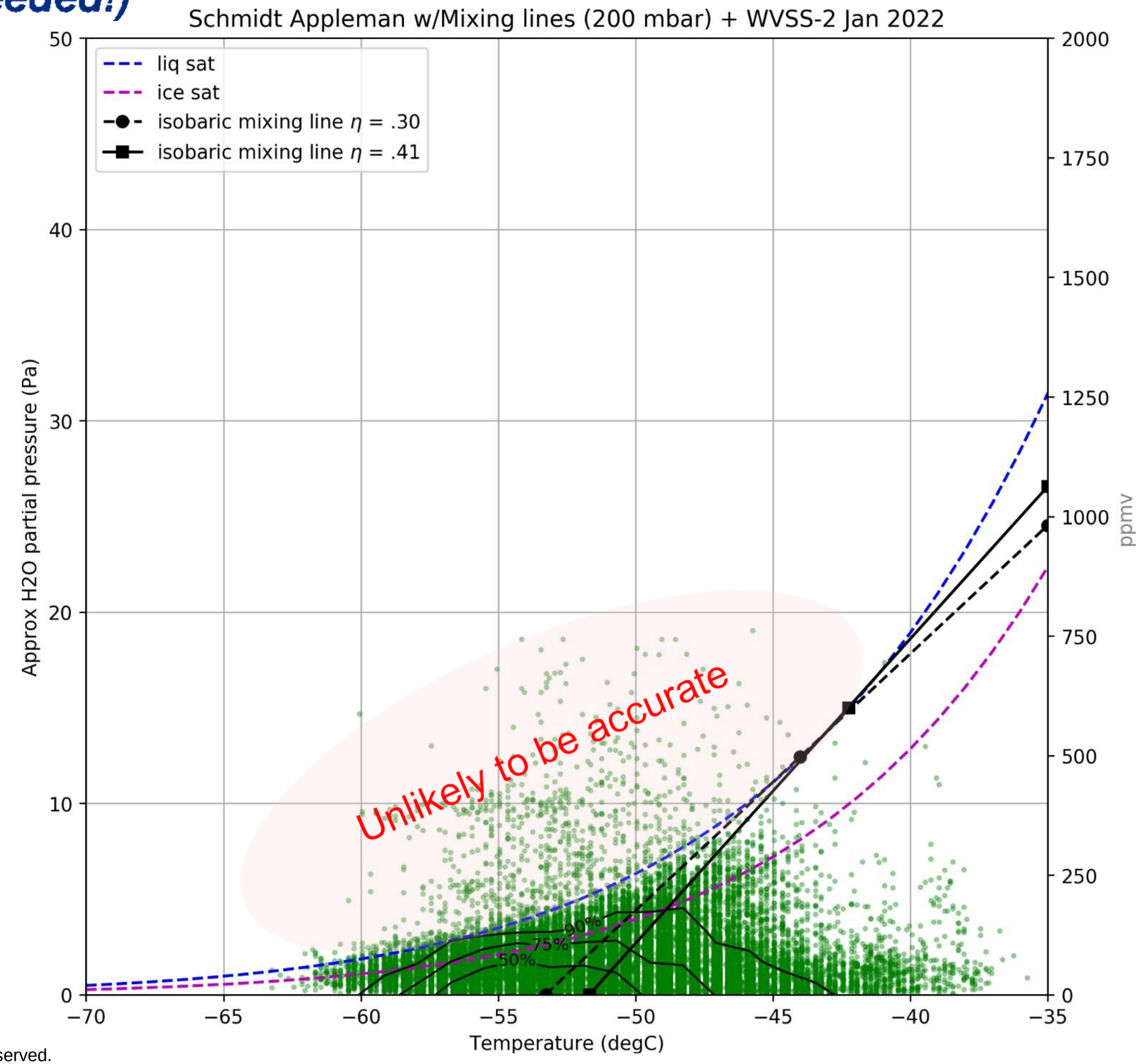
Water vapor sensor which can measure down to 20 ppmv would capture most ice supersaturation conditions where commercial airplanes fly



# Water vapor spans over 4 orders magnitude in concentration (ppmv)



# How is the WVSS-2 performing in upper troposphere?
## *(improvement needed!)*



## Global Model Treatment of Water Vapor needs improvement
### *(e.g., US GFS,UKMO,ECMWF)*

Likely issues:

- Vertical levels every 50 mb insufficient
- Horizontal at 0.25 degree insufficient
- Microphysics insufficient to capture near cloud supersaturation structure
- Subgrid processes important
- Dry bias

# Conclusions

- Measuring UT water vapor is difficult, but we don’t need stratospheric quality
- We’ve made some progress in bounding the range of water vapor concentration measurements needed
- A commercial water vapor sensor does not exist that meets our needs
- Current models are insufficient in identifying ISSLs or the RHI levels as well as we would want to robustly identify and avoid the most persistent contrails
- Industry/airline participation is required to make measurements in commercial service to confidently mitigate persistent contrail impacts

# Next Steps

- The government research labs and industry need to research and prototype sensors
  - Ongoing discussions within measurement community
- Explore development of prototype humidity sensor accurate in range 20 ppmv to 10000+ ppmv
  - Provide better measurements (T, RHi) at cruise altitudes for contrail mitigation
  - Provide better measurements at lower altitudes for weather forecasting
- With such data available for model evaluation and assimilation into forecasts, improve forecast models for more robust calculations
- Need to improve handling of clouds, aerosols, specific aircraft, etc. in model calculations of contrail impact